REPORT SAMSO-TR-76-118

(12)

Pitot Pressure Profile Measurement at the Exit of Very Small Nozzles

ADA 027497

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4 June 1976

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Prepared for
SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract F04701-75-C-0076 with the Space and Missile Systems Organization, Deputy for Advanced Space Programs, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by W. R. Warren, Jr., Director, Aerosphysics Laboratory. Lt. Ronald C. Lawson, SAMSO/YAPT, was the project officer.

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FOR THE COMMANDER

Ronald C. Lawson

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SAMSO-TR-76-118	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PITOT PRESSURE PROFILE MEASUREMENT AT THE EXIT OF VERY SMALL NOZZLES,		5. TYPE OF REPORT & PERIOD COVERED Interim rept.,
		6. PERFORMING ORG. REPORT NUMBER TR-0076(6240-10)-3
7. AUTHOR(s) Robert L. Varwig, Donald A. Durran and Shaowen W. Liu		8. CONTRACT OR GRANT NUMBER(s) F04701-75-C-0076
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space and Missile Systems Organization Air Force Systems Command Los Angeles, Calif. 90009		12. REPORT DATE 4 June 1976
		13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Pitot Pressure
Wind Tunnel
Measurements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Pitot pressure profile measurements at the exit plane of a nozzle are used to characterize the flow properties of nozzles. For very small nozzles, where the boundary layer is a significant part of the nozzle, the pitot pressure profile obtained when the probe is traversed across the nozzle exit displays peculiar properties. Close to the nozzle exit, at the edge of the nozzle, there are sharp peaks in the profile, and there is a lower pressure on the centerline than closer to the wall. The former effect is attributed to flow separation caused by the traversing probe, which

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

18 19 6 9 14 10 15 11 12 16p

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

is large relative to the scale of the flow nonuniformities, as in the case of a forward facing step. The latter effect is caused by the boundary layer, which changes the effective contour of the nozzle wall. In the 0.060-in.-diam conical nozzle of this study, the boundary layer changed the shape from conical to that approximating the first third of a Mach 6 contoured nozzle.

PREFACE

The authors thank M. E. Gerard and T. L. Felker for carrying out the nozzle measurements, and Dr. Harold Mirels for his skilled guidance in interpreting the data.

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FIGURES

I. INTRODUCTION

In order to characterize the flow properties of wind tunnel nozzles, it is generally quite satisfactory to measure the pitot pressure. From these measurements and a knowledge of the plenum conditions, the Mach number and all other flow properties can be deduced by using the Rayleigh equation. However, when the nozzle becomes very small, two effects begin to influence the observed pitot pressure: (1) the boundary layer causes a variation in free-stream stagnation pressure, and (2) the probe geometry may be large compared with transverse flow variations. The latter causes difficulties in the evaluation of probe data. In this report, observed pitot pressure profiles for very small nozzles are shown, and the results are described in terms of boundary layer growth and probe interaction.

II. EXPERIMENTAL RESULTS

The pitot pressure profile for a conical nozzle is shown in Fig. 1 for probe scans at the nozzle exit plane and at several positions progressively further downstream from the nozzle exit. The nozzle exit diameter/probe diameter ratio is 22; i.e., the nozzle is large relative to the pitot pressure probe size. Also shown in Fig. 1 are the computed boundary layer and boundary layer displacement thickness. Because the boundary layer displacement thickness is thin, it has no important effect on the effective nozzle shape. As a result, the pitot profiles display relatively "normal" behavior. The flow is slightly under-expanded. At the nozzle exit, there is essentially source-type flow (nearly flat pitot pressure profile because the nozzle angle is small) and a boundary layer characterized by decreasing pitot pressure that results from the loss of dynamic pressure as speed decreases close to the wall. Profiles further downstream display "ears" (believed to be caused by inward propagating oblique shock waves) that result from the continuing expansion of the flow after it leaves the nozzle. These oblique shock waves intersect at about 1.38 in. aft of the exit plane and produce the high pressure peak observed there. For these flow conditions, plenum pressure was 645 Torr He at a temperature of 1200 K. Exit Mach number on the centerline was 3.97.

When the nozzle is very small, the boundary layer may become a significant part of the nozzle. The predicted pitot pressure profile at the nozzle exit determined from the boundary layer properties is shown in Fig. 2 together with the measured pitot pressure profile for a conical nozzle 0.060 in. in diameter and a pitot probe 0.008 in. in diameter. The remainder of the pitot pressure profiles for various axial distances from the nozzle exit are shown in Fig. 3. The character of these profiles is much different from that observed for the larger nozzle. At the nozzle exit, there are very sharp peaks close to the edges of the nozzle. In the middle, between the two peaks, the pitot profile is inverted from that expected for source-type

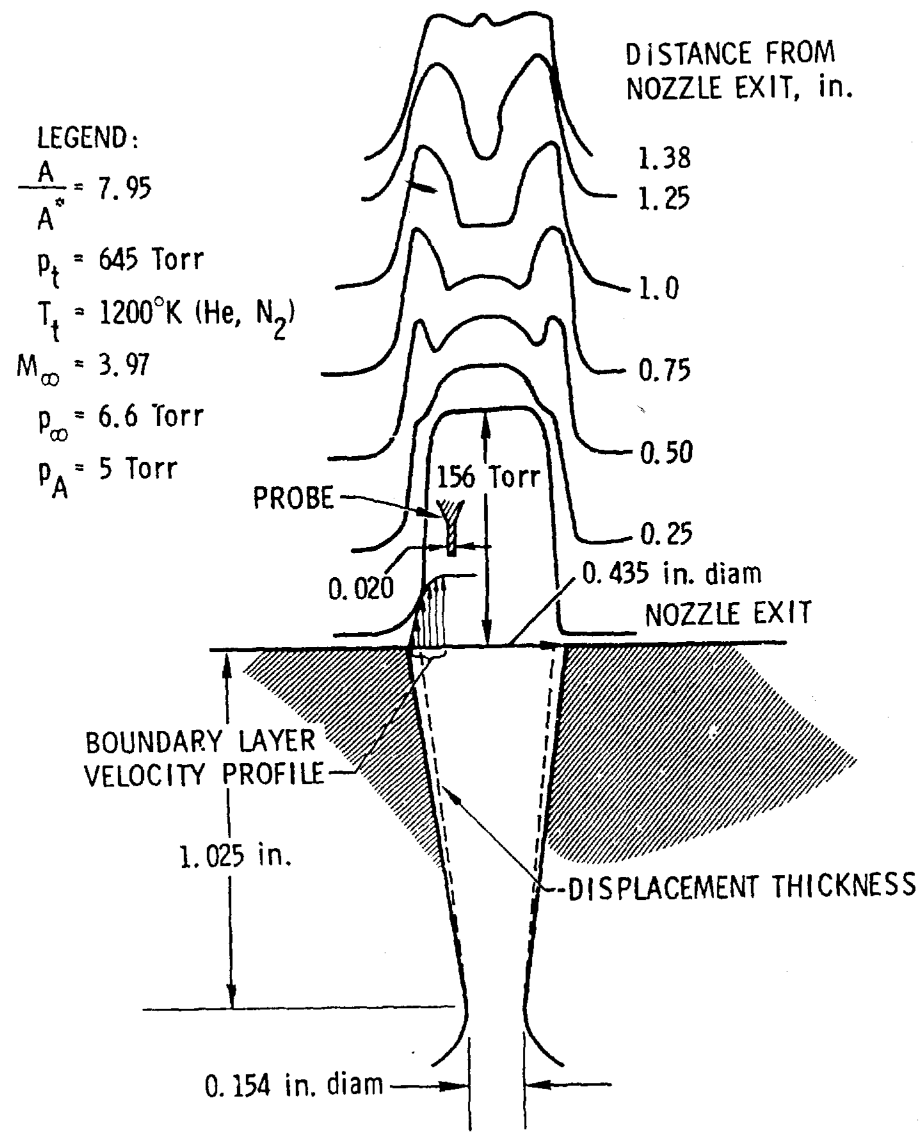


Figure 1. Pitot Pressure Profiles for Conical Nozzle Aft of Exit Plane

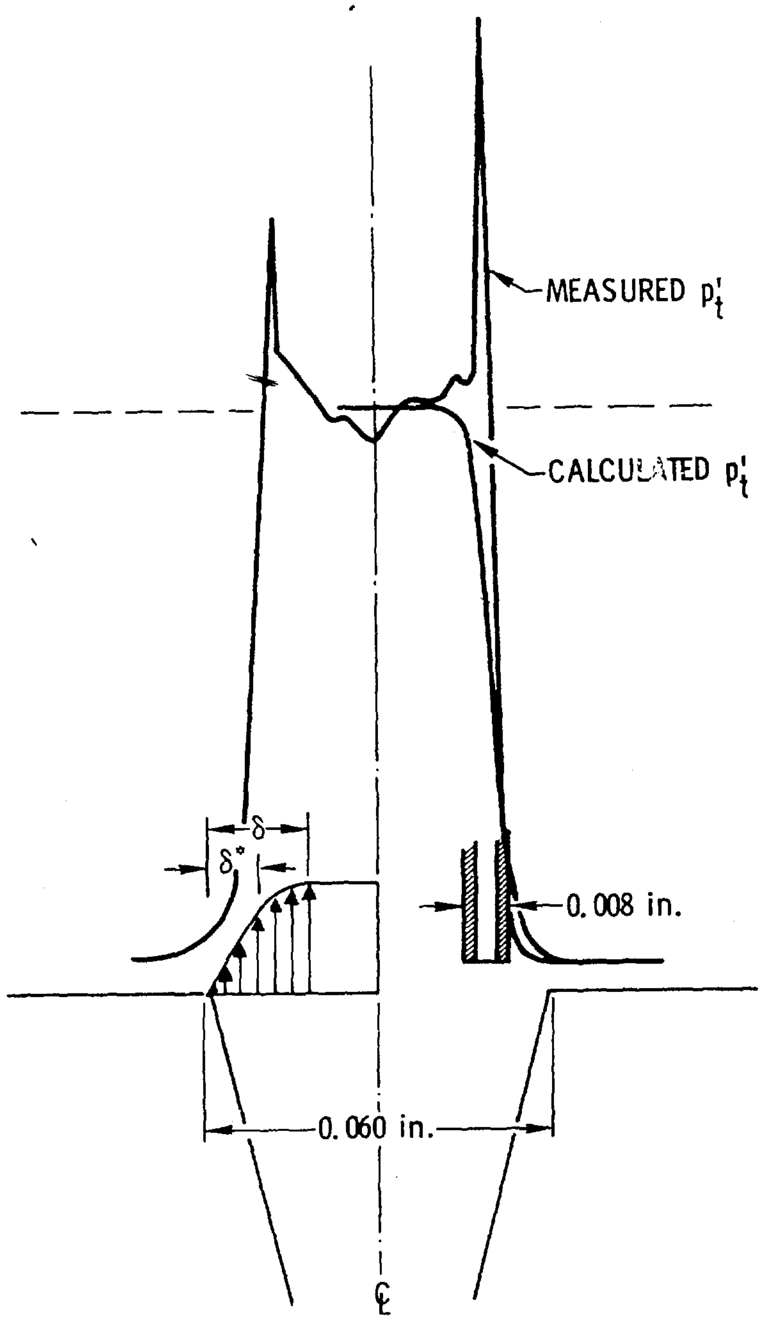


Figure 2. Predicted and Observed Pitot Pressure Profiles Computed from the Boundary Layer Profile at the Exit of a Conical 0.060-in.-diam Nozzle. Helium, plenum pressure = 10 atm, $A/A^* = 35$, $M = 6.7$.

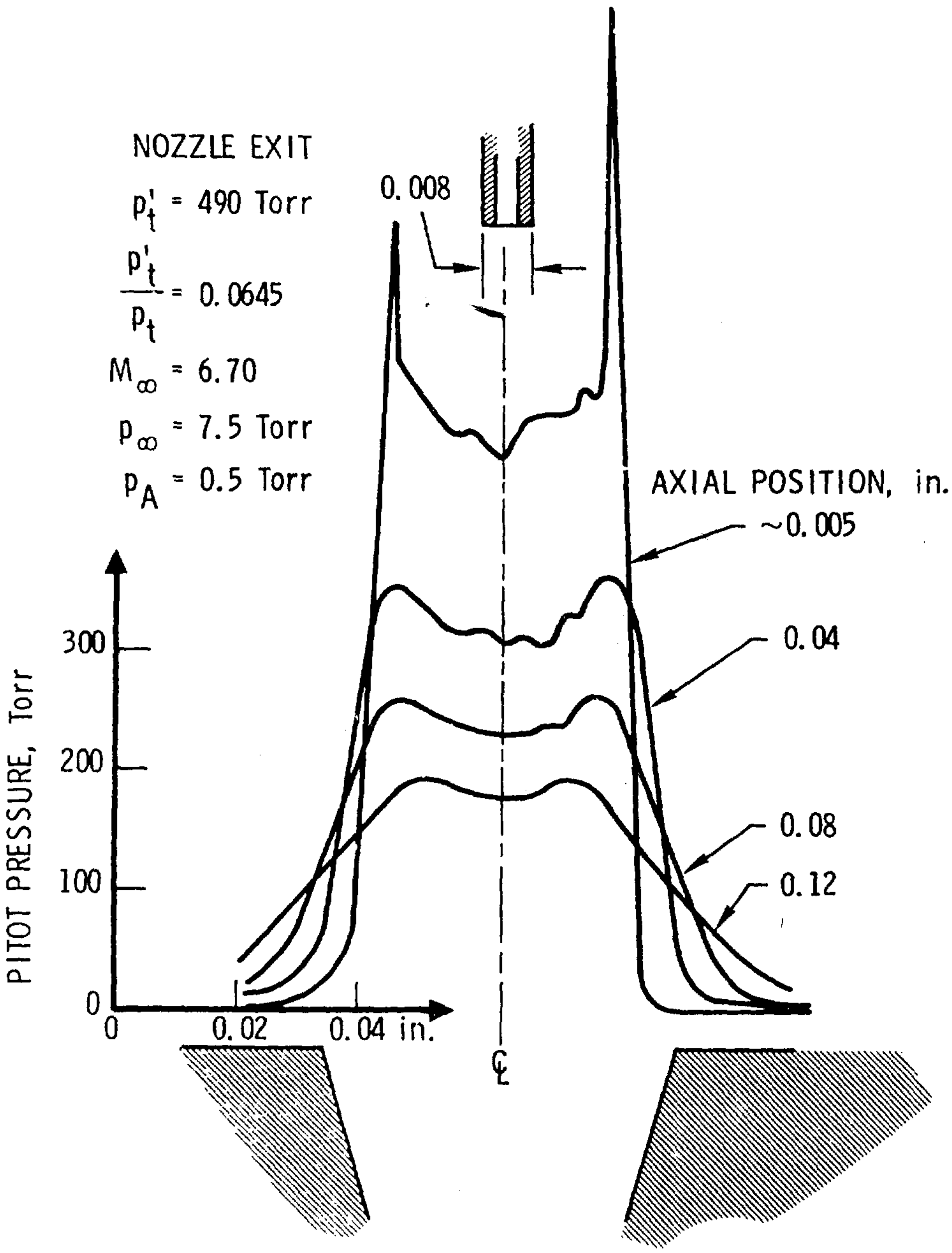


Figure 3. Pitot Pressure Profiles for a Very Small Conical Nozzle (0.060-in.-diam exit)

flow. (For source-type flow, the pitot pressure profile is convex upward, which reflects the increase in Mach number with distance from the centerline at a fixed axial distance downstream from the nozzle exit.) The observed pitot pressure profile, however, is concave downward at the centerline. The intense peaks disappear, however, when the probe is scanned further downstream. Also, as shown in Fig. 4, the peaks disappear when the plenum pressure is reduced, a condition that increases viscous effects in the nozzle flow.

The observed peaks are not associated with oblique shock waves that originate from an over-expanded jet (as in Fig. 1). The ambient pressure is much lower than the nozzle exit pressure, and the flow is in fact underexpanded. By increasing ambient pressure, as shown in Fig. 5, oblique shock waves can be produced.

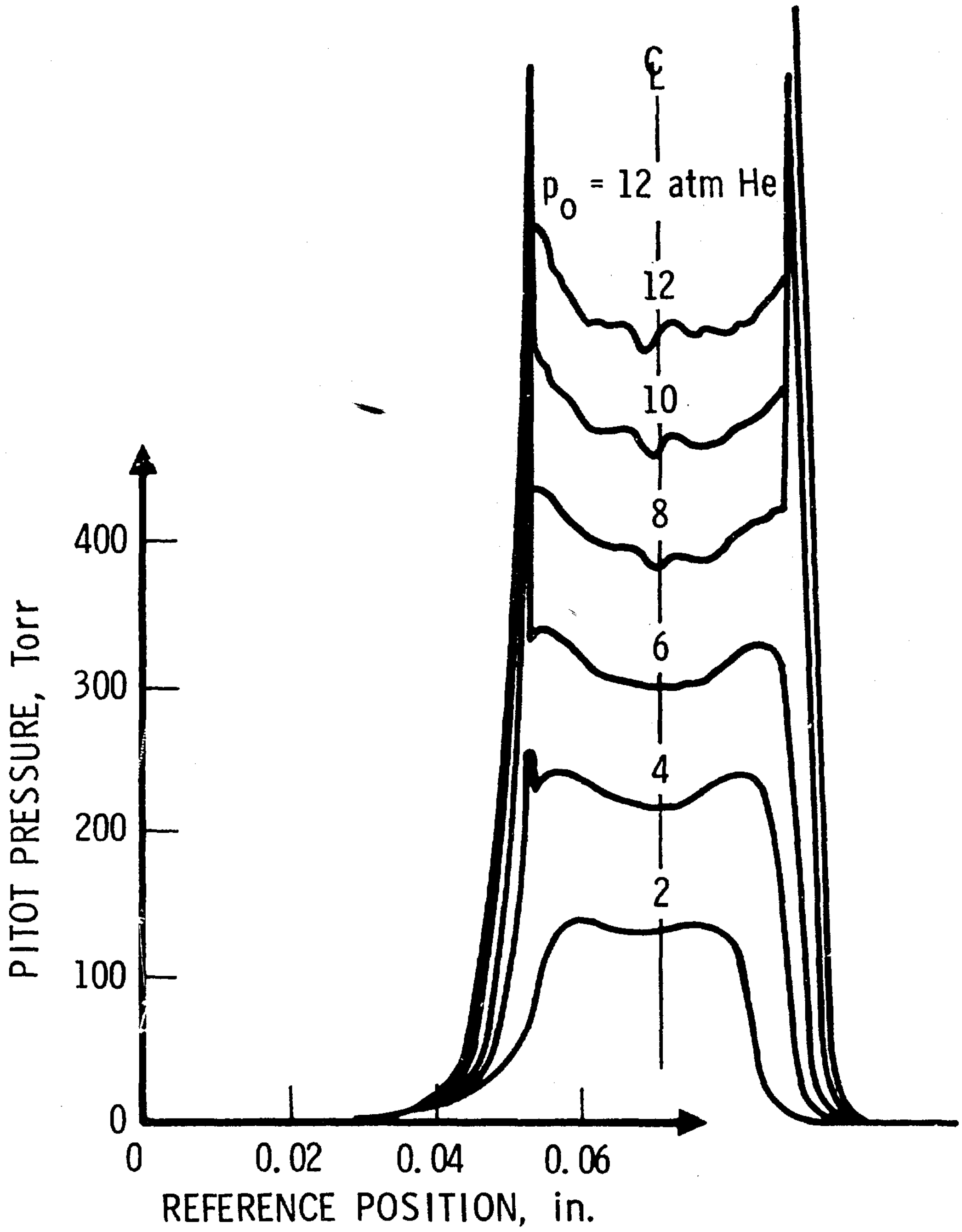


Figure 4. Pitot Pressure Profile at Nozzle Exit for Various Plenum Pressures. Helium, ambient pressure = 0.5 Torr, probe position 0.005 in. aft of nozzle exit.

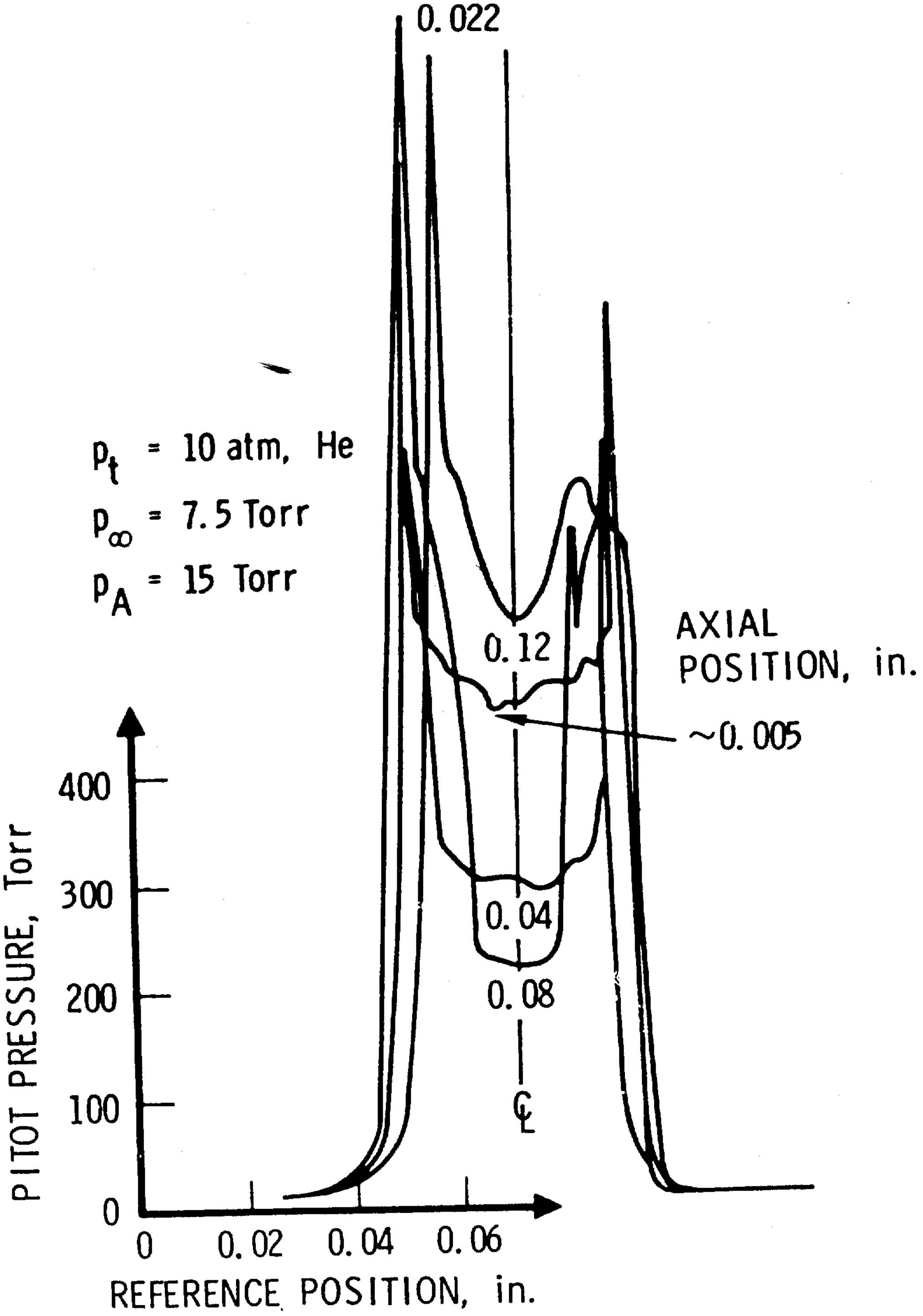


Figure 5. Pitot Pressure Profile for Over-Expanded Flow. Note evidence of oblique shock waves rising to match free-stream pressure to ambient pressure.

III. DISCUSSION

Unform parallel flow from a nozzle into ambient pressure just equal to the nozzle exit pressure will spread gradually to the point of closure, as shown in Fig. 6. The distance for this to occur is given approximately as

$$x_w = R\sqrt{Re}/5$$

where R is the nozzle exit radius. However, if the nozzle is an uncorrected diverging nozzle, or if the ambient pressure is different from the exit pressure, or if the flow is nonuniform at the exit because of the boundary layer, for example, the relation for x_w overestimates this length. When nozzle flow diverges or when ambient pressure is much lower than nozzle exit pressure, the flow speed on the axis will begin to decrease much faster than predicted by the closure calculation. When the ambient pressure is higher than the nozzle exit pressure (over-expanded nozzle flow), oblique shock waves originate at the exit to match the exit pressure to the higher ambient pressure.

The diagnostic technique used in this study is the pitot pressure probe. The pitot pressure or stagnation pressure is sensitive to location with respect to the oblique shock wave (Fig. 6b). The stagnation pressure aft of the oblique shock is larger than that sensed ahead of it because entropy increase is a cubic function of shock pressure ratio. Thus, compression by a single shock wave for the same initial and final conditions produces a much greater entropy change than that in which the compression is accomplished through two weaker shocks. Hence, the total pressure loss through a single normal shock (the bow shock for the forward probe) is greater than that for the probe aft of the oblique shock because compression is through the oblique shock and then through a bow shock. In the limit of a completely isentropic compression, there would be no loss of total pressure. Thus, the total pressure observed

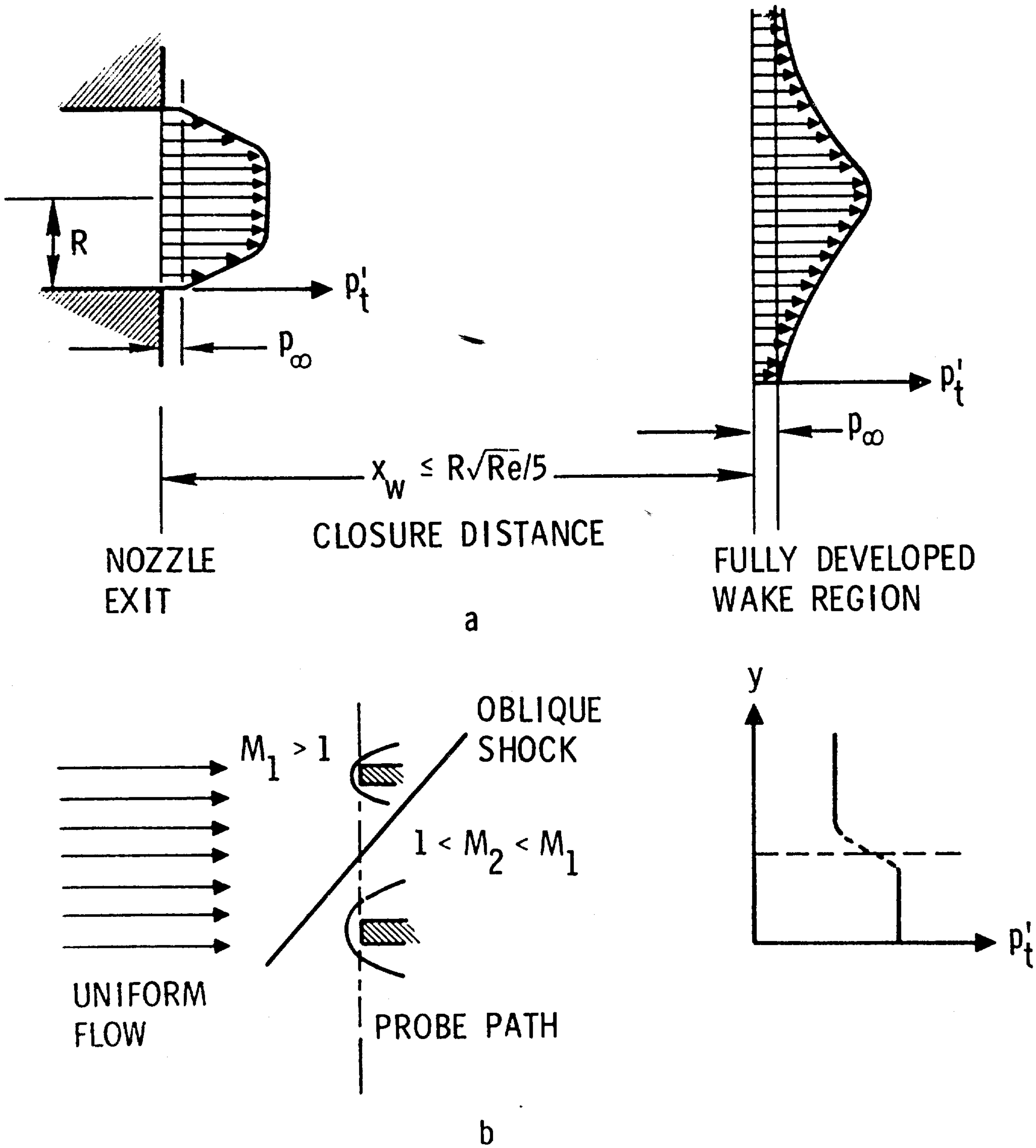


Figure 6. Uniform Flow Effect (a) and Oblique Shock Effect (b) on p_t'

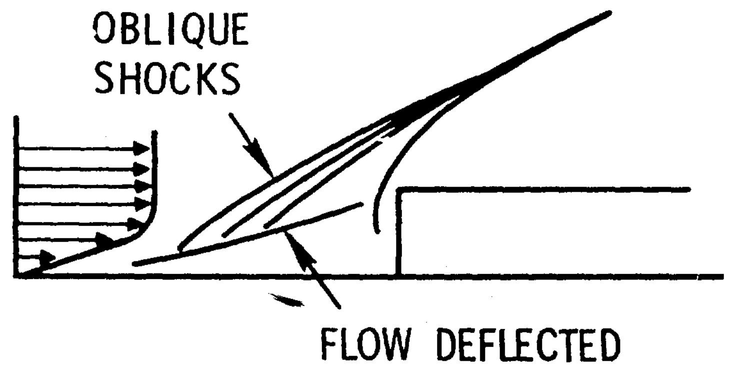
aft of the oblique shock is higher than that before the shock as the compression is more nearly isentropic.

The nozzle flows of Fig. 1 are examples of simple diverging nozzle flow. Because of the divergence, the pitot pressure on the axis begins to decrease downstream from the nozzle exit, and the flow becomes over-expanded. Thus, oblique shock waves originate in the downstream region and converge toward the axis. The pitot pressure profiles represent the relatively uniform flow at the nozzle exit, including the boundary layer effects. Downstream where oblique shock waves appear, the pitot pressure, where measured aft of the oblique shock waves, is higher, and thus forms the "ears" on the profiles. When the waves converge, about 1.38 in. from the nozzle, the flow is compressed threefold. The compression is therefore more efficient, and observed pitot pressure is higher still.

For these measurements, the gradient in velocity in the flow is small relative to the size of the pitot probe. Thus, the pitot probe is in essentially uniform flow for each instantaneous measurement. For the measurements made at the exit of the very small nozzle (Figs. 2 through 5), the probe is large relative to the scale of the nonuniformity, the velocity, and density gradients in the boundary layer. Therefore, a probe-flow interaction occurs similar to that observed by Chapman, Kuehn, and Larson[1] and Sedney and Kitchens[2] for forward facing steps. The interaction is indicated in Fig. 7. When the probe is large relative to the scale of the flow nonuniformity, pressure feeding upstream in the subsonic portion of the nonuniform flow deflects the flow forward of the probe, which generates oblique shock waves. The probe aft of the oblique shocks thus measures a higher total of stagnation

[1] D. R. Chapman, D. M. Kuehn, and H. K. Larson, Investigation of Separated Flows in Supersonic and Subsonic Streams with Emphasis on the Effect of Transition, NACA Report 1356 (1958).

[2] R. Sedney and C. W. Kitchens, The Structure of Three-Dimensional Separated Flows in Obstacle-Boundary Layer Interactions, BRL Report No. 1791, USA Ballistic Research Laboratories (June 1975).



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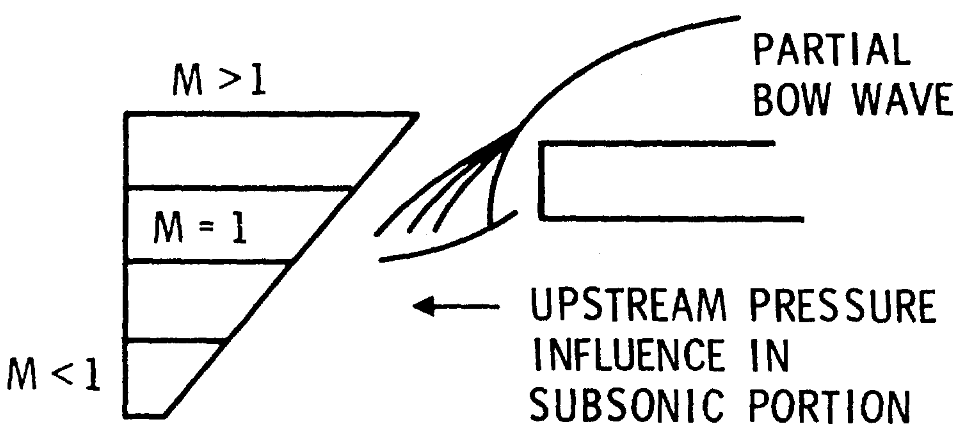

b

Figure 7. Probe-Flow Interaction. a. Example of interaction, a forward facing step. b. Finite probe in nonuniform flow.

pressure. When the flow moves far enough from the wall that the flow becomes uniform around the probe, the pressure decreases to that of a normal shock wave forward of the probe.

When plenum pressure is reduced, Reynolds number decreases, the flow becomes more viscous, and the scale of the nonuniformity (the boundary layer here) becomes large relative to the probe size. Then, the probe is again in essentially uniform flow. Thus, the pressure peaks disappear, as shown in Fig. 4 for lower plenum pressures.

Downstream from the nozzle exit, the scale of the nonuniformity quickly increases as the flow expands from the nozzle. The probe is again small relative to the flow gradient scale, and there is no complicated interaction between flow and probe. Thus, the sharp peaks disappear further aft of the nozzle exit plane.

When the ambient pressure exceeds the jet exit pressure such that oblique matching shock waves originate at the nozzle exit, the nonuniformity scale is somewhat confined and preserved for some distance aft of the exit plane. Thus, the sharp peaks that previously appeared only at the nozzle are then also observed together with the matching oblique shock waves.

The inverted character of the profiles closer to the center of the nozzles results from the contouring effect of the boundary layer in the nozzle. The nozzle boundary layer in nozzle exits 0.060 in. in diameter is shown in Fig. 8. The displacement thickness, which provides the boundary for the inviscid flow, is contoured. The contour approximates that which would be obtained in the first third of a Mach 6 nozzle. Hence, the Mach number on the centerline would be the highest obtained downstream of the limiting characteristic in a contoured nozzle, or simply the highest attained by the axial flow in the expanding nozzle. The Mach number off the axis is always lower because the flow in this region is gradually accelerated to the centerline value. The pitot pressure that reflects lower Mach number flow off axis increases as the probe moves out of the axial flow.

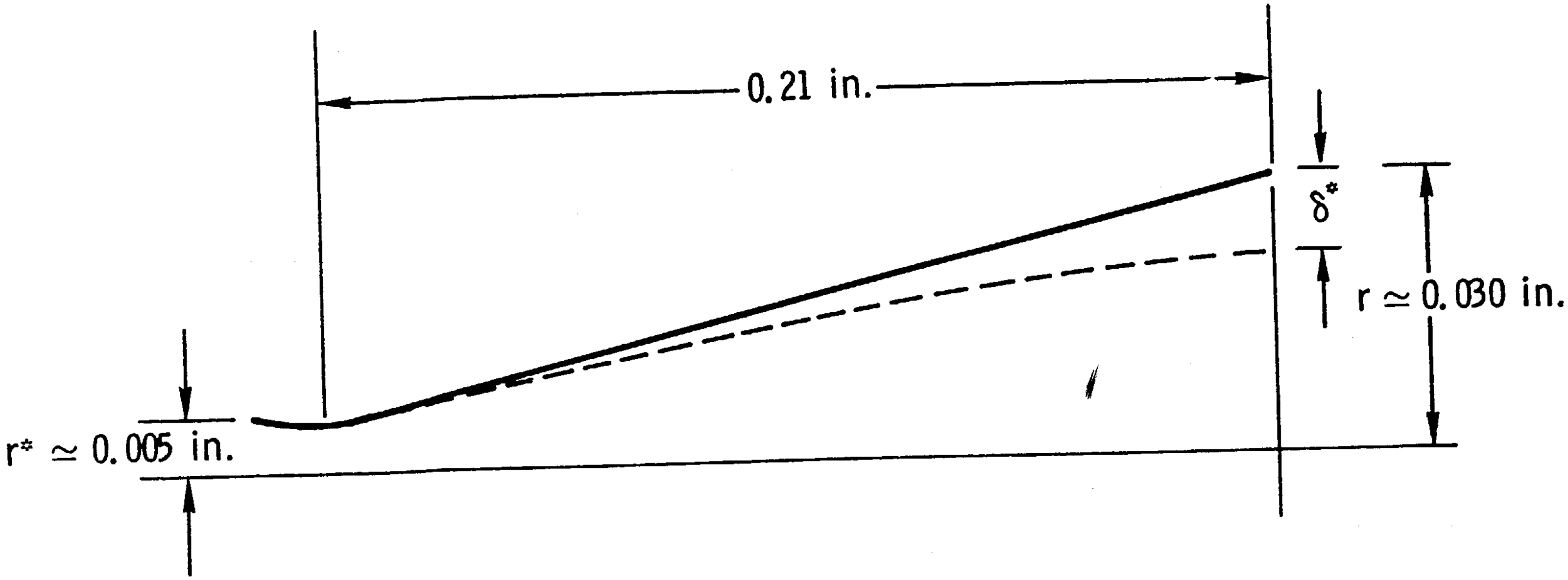

Figure 8. Axisymmetric Conical Nozzle and Boundary Layer Displacement Thickness δ^*. The displacement thickness contours the nozzle.

IV. CONCLUSIONS

Pitot pressure profiles measured at the exit of very small axisymmetric nozzles have sharp peaks close to the nozzle walls and are inverted from those expected for source flow (the nozzles are conical) over the central portion of the nozzle flow. The peaks are attributed to interaction between the probe and the flow when the probe is large relative to the scale of nonuniformity in the flow. When the probe is near the wall, for example, it may be considered as a forward facing step. The inverted profile is caused by the contouring effect of the wall boundary layer growing in the nozzle. The displacement layer converts the conical nozzle to a cut-off contoured nozzle. For such a nozzle, the profile would be expected to be inverted from that for source flow.

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